Journal of Sound and Vibration 425 (2018) 221–238

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Adaptive fault feature extraction from wayside acoustic signals from train bearings

Dingcheng Zhang [a,*], Mani Entezami [a], Edward Stewart [a], Clive Roberts [a], Dejie Yu [b]

[a] School of Engineering, University of Birmingham, Birmingham, B152TT, United Kingdom
[b] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, 410082, China

ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 30 March 2018
Accepted 5 April 2018

Keywords:
Wayside acoustic detection
Train bearing
Improved singular value decomposition
Savitzky-Golay smoothing filter
Resonance-based Signal Sparse Decomposition

ABSTRACT

Wayside acoustic detection of train bearing faults plays a significant role in maintaining safety in the railway transport system. However, the bearing fault information is normally masked by strong background noises and harmonic interferences generated by other components (e.g. axles and gears). In order to extract the bearing fault feature information effectively, a novel method called improved singular value decomposition (ISVD) with resonance-based signal sparse decomposition (RSSD), namely the ISVD-RSSD method, is proposed in this paper. A Savitzky-Golay (S-G) smoothing filter is used to filter singular vectors (SVs) in the ISVD method as an extension of the singular value decomposition (SVD) theorem. Hilbert spectrum entropy and a stepwise optimisation strategy are used to optimize the S-G filter's parameters. The RSSD method is able to nonlinearly decompose the wayside acoustic signal of a faulty train bearing into high and low resonance components, the latter of which contains bearing fault information. However, the high level of noise usually results in poor decomposition results from the RSSD method. Hence, the collected wayside acoustic signal must first be de-noised using the ISVD component of the ISVD-RSSD method. Next, the de-noised signal is decomposed by using the RSSD method. The obtained low resonance component is then demodulated with a Hilbert transform such that the bearing fault can be detected by observing Hilbert envelope spectra. The effectiveness of the ISVD-RSSD method is verified through both laboratory field-based experiments as described in the paper. The results indicate that the proposed method is superior to conventional spectrum analysis and ensemble empirical mode decomposition methods.

1. Introduction

In recent years, growth in passenger rail travel has dramatically increased. This demand has been driven by a number of factors including economic mobility, improved punctuality, and increased reliability. In order to sustain this growth, safety and reliability of railway transportation systems have become points of focus for the industry. Train bearings, are key components of the vehicle that support the whole weight of the train and operate at high speeds. Faults easily occur in train

* Corresponding author.
E-mail address: railcm@contact.bham.ac.uk (D. Zhang).

https://doi.org/10.1016/j.jsv.2018.04.004

bearings and result in economic loss or even casualties. Hence, fault detection in these key components plays a significant role in maintaining and continuing to increase rail's role in transportation networks.

Recently, many technologies have been suggested as suitable candidates for monitoring train axle-bearings without needing to disassemble them for inspection. Some technologies, such as oil monitoring [1] and vibration-based detection [2,3], are vehicle-mounted. These provide high quality information but require sensors and equipment to be fitted to every bearing on every vehicle. Acoustic emission [4] and hot axle box [5] detection systems can be fitted to one location in the network, but the former requires physical access to the track, while the latter is only suitable for detecting late stage faults [6]. Wayside acoustic detection is another technology that is becoming increasingly popular because one monitoring station will observe multiple vehicles, no physical track access is required in order to install the equipment, and detection is at an earlier stage than its thermal counterpart.

Acoustic waves are vibrational energy signals that are transmitted from the bearings via an elastic medium, i.e. through the air. If there is a fault in the axle-bearing, repeated impulse signals will occur in the vibration signal observed. Thus, train bearing faults can be detected by extracting these impulse signals. However, in this application, fault feature signals are often masked by high levels of background noise (e.g. vehicle noise, environmental noise, or aerodynamic noise, etc. [7]). Furthermore, they are also susceptible to harmonic interference.

To overcome this problem, researchers have proposed many methods. Wang et al. [8] use a variable FIR filter to obtain the fault feature signal after estimating the instantaneous frequencies. Combining the stochastic resonance method with multiscale noise tuning, He et al. [9] proposed the adaptive stochastic resonance method to enhance weak defect information. Zhang et al. [10] proposed a time-frequency filter with thresholds to separate the wayside acoustic signal and then applied an inverse STFT to obtain a de-noised signal. These methods use a known centre frequency band to extract the fault feature signal. However, centre frequencies for fault features in wayside acoustic signals are particularly difficult to identify due to high levels of background noise and harmonic components. Additionally, the methods described above may fail to detect train bearing faults when the fault feature signals have centre frequency bands that align with strong noise components.

Using different oscillatory behaviours at different frequencies within the signal, the RSSD method can decompose the wayside acoustic signal into high resonance and low resonance components [11]. Fault feature signals generated by the bearings have low levels of oscillatory behaviour and thus the bearing fault information can be found in the low resonance component [12]. The method has been successfully demonstrated in fault diagnosis systems based on vibration analysis [13,14], however, the high levels of background noise in wayside acoustic signals normally result in poor decomposition results [15].

The singular value decomposition (SVD) method is the one of most commonly used denoising techniques. However, the parameter selection of the method is an intractable problem. Additionally, the traditional SVD method has limited effectiveness when the target signal has a high level of noise. To overcome these issues, the Savitzky-Golay smoothing filter used in Ref. [16] is applied to the SVs obtained by decomposing the signal using the SVD theorem. The quality of the result is, however, directly affected by the parameters of the S-G filter [17]. Hence, in this paper, envelope spectrum entropy [18,19] is introduced to construct the objective function, and the stepwise optimisation strategy (SOS) [20–22]is used to adaptively select the parameters of the S-G filter.

In this paper, the parameters of the SVD method are optimised so that the correct SVs can be obtained. Envelope Spectrum Entropy and a stepwise optimisation strategy are then used to adaptively select the parameters of the S-G filter. The de-noised signal is then obtained using the filtered SVs. The de-noised signal is decomposed into high and low resonance components using the RSSD method, the parameters of which are optimised using a genetic algorithm. Finally, the low resonance component is subjected to Hilbert envelope demodulation and train bearing faults can be detected by observing the Hilbert envelope spectrum. Analysis of the results of experiments presented in this paper indicates that the ISVD-RSSD method can be used to effectively extract fault feature signals and to enhance weaker fault signals.

This paper is organised as follows: In Section 2, the ISVD method is introduced. In Section 3, the RSSD method is introduced. Wayside acoustic detection based on the ISVD-RSSD method is presented in Section 4. In Section 5, Section 6 and Section 7, the simulation, laboratory and field experiments' results using the proposed method are demonstrated. The conclusions of this paper are presented in the final section.

2. Improved singular value decomposition for wayside acoustic signal

2.1. Improved singular value decomposition

A wayside acoustic signal $\mathbf{x} = (x_1, x_2, \cdots, x_N)$ can be represented as the sum of a fault feature signal $\mathbf{y} = (y_1, y_2, \cdots, y_N)$ and a noise signal $\mathrm{n} = (n_1, n_2, \cdots, n_N)$, which includes all non-fault related components (i.e. includes the sound of normal bearing operation). The Hankel matrix $\mathbf{X}$ can be constructed as shown in Eq. (1) [23].